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Search History

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☐ 1. Document ID: US 6255817 B1

L7: Entry 1 of 8   File: USPT   Jul 3, 2001

US-PAT-NO: 6255817
DOCUMENT-IDENTIFIER: US 6255817 B1

TITLE: Nuclear magnetic resonance logging with azimuthal resolution

DATE-ISSUED: July 3, 2001

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Poitzsch; Martin E.	Sugar Land	TX		
Speier; Peter	Stafford	TX		
Ganesan; Krishnamurthy	Sugar Land	TX		
Chang; Shu-Kong	Sugar Land	TX		
Goswami; Jaideva C.	Houston	TX		

US-CL-CURRENT: 324/303; 324/300

| Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | Claims | KWIC |
| Draw. Desc | Image |

☐ 2. Document ID: US 6215304 B1

L7: Entry 2 of 8   File: USPT   Apr 10, 2001

US-PAT-NO: 6215304
DOCUMENT-IDENTIFIER: US 6215304 B1

TITLE: NMR sensor

DATE-ISSUED: April 10, 2001

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Slade; Robert Andrew	Witney			GBX

US-CL-CURRENT: 324/303; 324/318

| Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | Claims | KWIC |
| Draw. Desc | Image |

☐ 3. Document ID: US 6028429 A

US-PAT-NO: 6028429
DOCUMENT-IDENTIFIER: US 6028429 A

TITLE: Composite MRI antenna with reduced stray capacitance

DATE-ISSUED: February 22, 2000

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Green; Charles	Holbrook	NY		
Votruba; Jan	Ridge	NY		
Eydelman; Gregory	West Hempstead	NY		
Damadian; Raymond V.	Woodbury	NY		

US-CL-CURRENT: 324/318; 324/322, 600/412

Full	Title	Citation	Front	Review	Classification	Date	Reference	Sequences	Attachments	Claims	KWIC
Draw Desc	Image

☐ 4. Document ID: US 5928229 A

US-PAT-NO: 5928229
DOCUMENT-IDENTIFIER: US 5928229 A

TITLE: Tumor ablation apparatus

DATE-ISSUED: July 27, 1999

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Gough; Edward J.	Menlo Park	CA		
Stein; Alan A.	Moss Beach	CA		

US-CL-CURRENT: 606/41; 606/42, 606/48, 607/101, 607/102

Full	Title	Citation	Front	Review	Classification	Date	Reference	Sequences	Attachments	KWIC
Draw Desc	Image

☐ 5. Document ID: US 5683384 A

US-PAT-NO: 5683384
DOCUMENT-IDENTIFIER: US 5683384 A

TITLE: Multiple antenna ablation apparatus

DATE-ISSUED: November 4, 1997

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Gough; Edward J.	Menlo Park	CA		
Stein; Alan A.	Moss Beach	CA		
Edwards; Stuart D.	Los Altos	CA		

US-CL-CURRENT: 606/41; 606/48, 607/101, 607/156

☐ 6. Document ID: US 5284144 A

L7: Entry 6 of 8   File: USPT   Feb 8, 1994

US-PAT-NO: 5284144
DOCUMENT-IDENTIFIER: US 5284144 A

TITLE: Apparatus for hyperthermia treatment of cancer

DATE-ISSUED: February 8, 1994

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Delannoy; Jose	Monsen Baroeul			FRX
Le Bihan; Denis	Rockville	MD		
Chen; Ching-nien	Catonsville	MD		
Levin; Ronald L.	Olney	MD		
Turner; Robert	Bethesda	MD		

US-CL-CURRENT: 600/412; 324/315, 600/422, 607/154

☐ 7. Document ID: US 5061838 A

L7: Entry 7 of 8   File: USPT   Oct 29, 1991

US-PAT-NO: 5061838
DOCUMENT-IDENTIFIER: US 5061838 A

TITLE: Toroidal electron cyclotron resonance reactor

DATE-ISSUED: October 29, 1991

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Lane; Barton G.	Belmont	MA		
Sawin; Herbert H.	Lexington	MA		
Smatlak; Donna L.	Arlington	MA		

US-CL-CURRENT: 219/121.59; 156/345, 204/298.17, 204/298.37, 204/298.38, 219/121.42, 219/121.43

☐ 8.   Document ID: US 4620155 A

L7: Entry 8 of 8   File: USPT   Oct 28, 1986

US-PAT-NO: 4620155
DOCUMENT-IDENTIFIER: US 4620155 A

TITLE: Nuclear magnetic resonance imaging antenna subsystem having a plurality of
non-orthogonal surface coils

DATE-ISSUED: October 28, 1986

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Edelstein; William A.	Schenectady	NY		

US-CL-CURRENT: 324/322; 324/318

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Term	Documents
(4 AND 6).USPT,PGPB,JPAB,EPAB,DWPI,TDBD.	8
(L4 AND L6).USPT,PGPB,JPAB,EPAB,DWPI,TDBD.	8

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L7: Entry 2 of 8   File: USPT   Apr 10, 2001

DOCUMENT-IDENTIFIER: US 6215304 B1
TITLE: NMR sensor

Abstract Paragraph Left (1):
An NMR sensor including a magnetic field generating assembly, an RF antenna, and a
plurality of ferrite members which couple with RF magnetic fields transmitted or
received by the RF antenna. The sensor is typically used in apparatus for performing
borehole measurements.

Brief Summary Paragraph Right (1):
The present invention relates to an NMR sensor.

Brief Summary Paragraph Right (2):
A measurement-while-drilling tool is described in EP-A-0581666 (Kleinberg) The tool
comprises a tubular drill collar; a drill head positioned at an axial end of the
drill collar; and an NMR sensor. The NMR sensor comprises a pair of tubular main
magnets (which generate a static (B.sub.0) magnetic field) each located in an
internal recess of the drill collar, and an RF antenna located in an external recess
in the drill collar between the main magnets. The RF antenna recess is optionally
filled with a magnetically soft ferrite to improve the efficiency of the antenna.

Brief Summary Paragraph Right (3):
An NMR well logging system is described in U.S. Pat. No. 4629986 (Clow et al.). A
pair of main magnets are separated by a gap in which a solenoid RF antenna is
symmetrically disposed. The solenoid has a core of high permeability ferrimagnetic
material (soft ferrite).

Brief Summary Paragraph Right (5):
In accordance with the present invention there is provided an NMR sensor comprising
a magnetic field generating assembly; an RF antenna; and a plurality of ferrite
members which couple with RF magnetic fields transmitted or received by the RF
antenna.

Brief Summary Paragraph Right (6):
The ferrite members boost the Q of the RF antenna and compensate for the effects of
eddy currents. Typically the ferrite members are soft ferrite members.

Brief Summary Paragraph Right (9):
Apart from minimising dimensional resonances, the provision of plural ferrite
members provides an additional degree of freedom in the geometrical arrangement of
the ferrite. Therefore the relative sizes and positions of the ferrite members can
be selected to optimise the B.sub.0 and RF field profiles. The effect of ferrite on
the B.sub.0 and RF field profiles has not previously been fully recognised in the
prior art. It is important that the B field shape is optimised to maximise radial
shell thickness to reduce susceptibility to lateral tool motions (such as vibration
and whirl) whilst maintaining sufficient signal-to-noise ratio. In particular,
unless care is taken in the design, the static magnetic field will tend to saturate
the soft ferrite, reducing its relative permeability to unity and negating any
improvements in RF efficiency. Similarly, the soft ferrite will modify the B.sub.0
field profile, thereby changing the shape and position of the sensitive volume from
which NMR signal arises. Both of these related effects must be considered in the
design of a real sensor.

Brief Summary Paragraph Right (10):
Various B0 field profiles are achievable by adjusting the size and axial position of

the soft ferrite members: it is possible to cancel the first and second order radial gradients to create a "radially optimised" field profile, as described by Hanley in U.S. Pat. No. 5471140, or alternatively to cancel the first order axial field gradient to generate an "axially optimised" field profile, as described in EP-A-0774671, or to shim the field for uniform BO magnitude for an "intermediate" field profile, as described by Slade in PCT/GB98/02398. Unlike this prior art, the BO field manipulation is achieved using the placement of soft ferrites only; no hard ferrite permanent magnet shims need be employed.

Brief Summary Paragraph Right (11):
Furthermore, in a similar fashion adjustment of the soft ferrite members can be used to reposition the small crescent-shaped resonant regions, known as "borehole lobes" and shown in FIG. 6, which can produce unwanted NMR signal from the borehole region. The lobes can be moved until they are partially or wholly within the outside diameter of the tool. In this way they cannot generate a significant borehole NMR signal.

Brief Summary Paragraph Right (12):
Typically the NMR sensor is an "inside-out" sensor which performs measurements on an external sample outside the space envelope of the magnetic field generating assembly and the RF antenna.

Brief Summary Paragraph Right (14):
The apparatus may be a wireline tool which performs measurements after the borehole has been drilled. However in a preferred example the apparatus is a measurement-while-drilling (MWD) tool which is provided with a drill head at an axial end of a support whereby the apparatus can carry out NMR measurements during drilling of the borehole. The tool may be a logging-while-drilling (LWD) or formation-evaluation-while-drilling (FEWD) tool in which the NMR information relating to the formation is stored on in-board memory for retrieval when the tool is returned to the surface. Alternatively a telemetry system may be provided and the NMR information is used to control the drill in real time (i.e. steering).

Brief Summary Paragraph Right (16):
Furthermore a typical MWD tool has a larger radius than a comparable wireline tool. Since the B.sub.0. strength scales approximately as the second power of the magnet mean radius, it is possible to space the main magnets farther apart in an MWD tool using larger diameter main magnets and thus regain some of the penetration depth.

Brief Summary Paragraph Right (17):
The ferrite members may be axially spaced and/or spaced at right angles to the axis of the tool. A primary consideration in the design of an NMR MWD tool is making the NMR measurement insensitive to the effect of lateral tool motions, such as vibration and whirl. To a first approximation it is clear that it will not be possible to re-focus the NMR signal in the sensitive region if the tool is displaced laterally (i.e. in a direction parallel to the radius) during the pulse sequence by a distance which is a significant proportion of the radial thickness of the sensitive shell. It is therefore necessary to select a B.sub.0 optimisation scheme and RF bandwidth such that the shell thickness is much larger than the maximum expected lateral displacement. Little is known about the precise motions of drilling tools down hole, but the typical range of displacement is from 1 to 10 mm at frequencies of a few Hz.

Brief Summary Paragraph Right (18):
Rotation periods are between 1 and 3Hz. The typical NMR mea0surement lasts from 50 ms to 1s, so these motions are significant. However, the flexible nature of the sensor according to the present invention ensures that it is possible to design a tool with a sensitive shell thicker than the maximum expected motion. The tool described in the preferred embodiment has a shell with a radial thickness about 20 mm and axial length about 50 mm.

Brief Summary Paragraph Right (19):
In comparison to a wireline borehole logging tool, an MWD tool has to be significantly stronger to support the drilling forces. In particular, as the sensor forms part of the drill collar, it has to be able to withstand the torsional and bending loads imposed by the rotating drilling action. It is therefore preferred that the entire sensor support structure is metal, such as stainless steel or titanium. However, the RF antenna will introduce localised parasitic eddy currents in the metallic structure of the tool which can seriously impair RF efficiency. It

is therefore necessary to consider how to minimise the impact of the all-metal structure on the RF field.

Brief Summary Paragraph Right (20):
The arrangement that gives the best mechanical strength and RF efficiency is achieved by winding the RF antenna as a solenoid in an external recess as described in EP-A-0581666. The skin depth in stainless steel at the typical operating frequency of 0.5 MHz is less than a few millimetres. Eddy currents will therefore flow in the surface of the drill collar under the RF coil, mirroring the driving current and effectively restricting the RF flux to the radial gap between the reduced drill collar outer diameter and the RF coil inner diameter. The RF coil diameter is made as large as possible consistent with the tool diameter, but it is desirable to make the coil recess as shallow as possible to minimise the loss in mechanical strength in this region. However, as the recess is made radially shallower, the gap decreases and the inductance of the RF transmit coil decreases, hence the RF field strength in the sensitive region for a fixed coil current decreases, hence requiring longer pulses, thus resulting in narrower bandwidth, reduced sensitive volume and lower signal strength. If the coil current is increased to compensate, the power requirement rises as the second power of current, so this too is undesirable. In practice the recess is made as deep as possible, consistent with adequate tool strength, and the loss in RF efficiency due to eddy currents is compensated by inserting soft ferrite into the gap between the RF coils and the recess base.

Brief Summary Paragraph Right (21):
This places constraints on the design of the NMR sensor and can result in reduced mechanical strength. Therefore in a preferred embodiment the apparatus further comprises a recess formed in the support, the recess having a base and a pair of axially spaced shoulders, wherein the ferrite members are located at least partially in the recess; and one or more strengthening members which are arranged between the ferrite members, coupled to the base of the recess, and coupled to each shoulder of the recess. The strengthening member(s) increase the torsional and bending strength of the tool. As a result the depth of the recess can be greater than in the prior art without decreasing the strength of the tool.

Brief Summary Paragraph Right (23):
Typically the RF antenna comprises a coil which is wound over the ferrite members.

Brief Summary Paragraph Right (24):
Typically the magnetic field generating assembly comprises a pair of axially spaced main magnets having opposite pole orientation (i.e. like poles facing each other), and the RF antenna is located axially between the pair of main magnets. This provides a rotationally invariant radial static magnetic field which is particularly important in a MWD tool.

Brief Summary Paragraph Right (28):
The choice of soft ferrite material is further complicated by the property of magnetostriction exhibited by all ferrite. This phenomenon is a microscopic change in the physical dimensions of the ferrite under the influence of magnetic field. After the application of an RF pulse, the ferrite structure "rings" like a bell as stored energy dissipates. In a practical design it is necessary to minimise the amount and duration of ringing as too much ringing can disable the NMR receiver. The most accurate NMR measurements are made when RF pulses in a CPMG sequence are applied as rapidly as possible. As the NMR echo is acquired at a point in time midway between RF pulses, it is necessary to minimise the system "deadtime"--the time taken for the receiver system to recover from an RF pulse. A high degree of magnetostriction will increase the deadtime, so it is desirable that the ferrite used has a low coefficient of magnetostriction. Unfortunately, NiZn ferrite has a coefficient of magnetostriction 3 to 5 times greater than MnZn ferrite. Therefore, if MnZn ferrite is used, the individual pieces must be small enough such that dimensional resonances are not excited--less than about 13 mm in all dimensions in the example given. Many more pieces will be required, but this can even be an advantage from a manufacturing standpoint.

Drawing Description Paragraph Right (2):
FIG. 1 is a schematic cross-section of a NMR measurement-while-drilling tool drilling a borehole;

Detailed Description Paragraph Right (2):

The sensor section 2 comprises a magnetic field generating assembly for generating a B.sub.0 magnetic field (which is substantially time invariant over the duration of a measurement), and an RF system for transmitting and receiving RF magnetic pulses and echoes. The magnetic field generating assembly comprises a pair of axially spaced main magnets 3,4 having opposite pole orientations (ie. with like magnetic poles facing each other), and three ferrite members 9,10 axially arranged between the main magnets 3,4. The ferrite members are made of "soft" ferrite which can be distinguished over "hard" ferrite by the shape of the BH curve which affects both intrinsic coercivity (H.sub.cj, the intersection with the H axis) and initial permeability (.mu..sub.i, the gradient in the unmagnetised case). Soft ferrite .mu..sub.i values typically range from 100 to 10000 whereas hard ferrite .mu..sub.i is about 1. Therefore the soft ferrite has large initial permeability (typically greater than 100, preferably greater than 1000). The RF system comprises a set of RF transmit antenna and RF receive antenna coil windings arranged as a central "field forming" solenoid group 13 and a pair of outer "coupling control" solenoid groups 14.

Detailed Description Paragraph Right (7):
The drill collar 8 is constructed by machining a stainless steel cylinder with a bore to receive the mud pipe 6, enlarging the inside diameter for the cylindrical main magnet poles 3,4 and milling eight axial pockets 23-30 in the outer radial periphery of the collar 8 separated by eight axial ribs (or webs) 31-38. This results in an annular recess in the outer periphery of the collar with a base 70 (shown in FIG. 1) and eight axial ribs 31-38 which project from the base 70 and extend between the two axial shoulders 71,72 of the recess. The soft ferrite members 9,10 are built up from arc segments mounted in the axial pockets 23-30. For instance the central member 9 is formed from eight arc segments 39-46. The axially oriented ribs 31-38 stiffen the reduced diameter section of drill collar under the RF coils. Surprisingly, the effect of the ribs 31-38 on the RF field profiles has been found to be quite negligible in the sensitive region by using commercial 3D FEA software to re-analyze the RF fields in the presence of the ribs 31-38.

Detailed Description Paragraph Right (10):
Each "coupling control" solenoid group 14 comprises a pair of receive coil winding groups 83,84 wound in the same sense as the field forming winding groups and a transmit coil winding group 85 wound in the opposite sense. All coils in both groups allocated to the transmit coil are series connected as are all those allocated to the receive coil. The coil and number of turns positions are selected to produce substantially uniform axially oriented RF flux across the sensitive volume, thus creating conditions for NMR, whilst simultaneously cancelling the mutual inductance of the transmit and receive coils. The system of "zero-coupling coils" is described in EP-A-0837338. Furthermore, as also described in EP-A-0837288, the design of the twin RF coil system is such that it does not generate any NMR signal within the borehole region (for example, from vestigial borehole lobes). Consequently, the present invention does not require the use of gradient coils to cancel borehole signal, as described in EP-A-0581666 (Kleinberg).

Detailed Description Paragraph Right (14):
As described above, the soft ferrite material is chosen with a high saturation flux density so that the static B0 field does not saturate the ferrite. The working point of the ferrite on the BH curve at each point within its volume therefore varies depending on the local magnetic field intensity due to the main magnet poles, but in all cases the working point is on the lower third to half of the initial linear gradient section. (The precise gradient and offset depend on the previous magnetic history and hysteresis characteristics of the ferrite). The slope of the BH curve is a measure of the relative permeability of the material, which is typically 200-6000 for soft ferrite grades suitable for the application. When alternating current is passed though the RF transmit coil at the resonant frequency during an RF pulse, the flux density within the ferrite is boosted by the permeability of the ferrite, and the ferrite is taken repeatedly around a minor hysteresis loop with each cycle of the RF. As long as the RF B1 field does not cause the ferrite to saturate, (ie: move out of the linear portion of the major BH curve) the RF flux density in the sensitive volume will be increased dramatically by the presence of the ferrite. Saturation is avoided by limiting the current density in the RF coils. Typically the increase in B1 flux density achieved, when compared with the same current in the same coil, without ferrite and without the stainless drill collar, will be a factor of 3-6, depending on coil geometry, and a factor of 6-12 over the flux density from the same current in the same coil, without the ferrite but with the drill collar. This is a very significant increase, resulting in a valuable saving in RF power.

Some of this power can then be used to shorten the RF pulses, increase the system bandwidth and thereby increase the volume of the sensitive shell, hence increasing SNR and resistance to lateral motion effects.

Detailed Description Paragraph Right (15):
The increased flux linking the RF coils as a result of the soft ferrite increases their inductance in a similar manner. It is therefore preferred that all the winding sections of both Tx and Rx coils are wound over ferrite and their inductances boosted in a similar way, so that the Tx-Rx mutual inductance of the "field forming" group is cancelled by the mutual inductance of the "coupling control" group, if zero coupling is to be achieved.

Detailed Description Paragraph Right (16):
Analysis shows that for this embodiment it is not possible to position all of the RF coils over the single central soft ferrite member 9 and still maintain approximately uniform RF field profiles across the sensitive volume. It is possible to place the field forming group 13 over the central shim, but the coupling control group 14 needs to be positioned separately, for example, axially above the central shim. For zero coupling to be achieved between the Tx and Rx coils, it is therefore necessary to add the extra pair of soft ferrite disk members 10 under the coupling control RF coil groups 14. Obviously, these extra ferrite members 10 affect the B0 field profile significantly. However, by returning to the B0 analysis, it is possible to adjust the length of the centre shim 13 slightly to correct for the field distortion created by the new ferrite pair 10. Being closer to the main magnet poles 3,4 the additional ferrite pair 10 are in stronger magnetic fields and are closer to saturation than the central ferrite member 9. If the material grade is selected carefully, however, the ferrite pair 10 will remain on the linear part of the BH curve over the majority of their volume and retain a relative permeability comparable with the central shim. The relative permeability of the ferrite members 9,10 is shown in a contour plot in FIG. 6. In this way, it is possible to iteratively optimise the RF coil design and to meet the twin field profile and near zero-coupling design requirement. In a possible alternative embodiment, the coupling control coil groups, and their associated soft ferrite, can be physically removed entirely from the vicinity of the sensor, for example into the electronics module. The electrical connection and function of the various coils remains identical. In this embodiment, the magnet field shape can either be adjusted using only the central ferrite shim, or by adding other ferrite shims as required. These additional ferrite shims do not necessarily have RF coils wound over them.

Detailed Description Paragraph Right (17):
The electronics 1 illustrated in FIG. 7 is typically housed in a series of hermetically sealed pockets in the drill collar 8 above or below the sensor elements. Critical components, such as the receiver preamplifier 50, are located as close as possible to the tuned RF receive coil. The main components of the electronics required to interface with the NMR sensor are: a RF transmitter amplifier 51 to drive the transmit antenna 52, a low noise receiver pre-amplifier 50 connected to the receive antenna 53, a digital spectrometer 54 to schedule pulses and detect echoes, an associated down-hole computer 58 to analyze and compress the data and control the tool, electronic memory 59 for data storage and optionally a telemetry system 55 consistent with the drilling environment, such as a mud-pulse system. Power for the electronics is typically derived from a turbine generator 56 driven by the mud flow, and is quite limited, typically to 100W, so some form of on-board energy storage 57 is also required as the power dissipation during a pulse sequence will often exceed the input power.

Detailed Description Paragraph Right (18):
In a first alternative embodiment, the ferrite members 9,10 each comprise a unitary member having eight inner slots which receive strengthening ribs extending only partially between the inner and outer radial peripheries of the ferrite. The central ferrite member of such an alternative is shown in FIG. 8 (which corresponds with FIG. 3). The ribs 31'-38' extend half way into the unitary block of ferrite 9'.

Detailed Description Paragraph Right (21):
In a fourth alternative embodiment (not shown) the axial ribs 31-38 are omitted from the central RF antenna recess and strengthening ribs are only provided in the main magnet recesses.

Detailed Description Paragraph Right (22):
In a fifth alternative embodiment (not shown), the axial ribs are omitted from both

the RF antenna recess and the magnet recess.

Other Reference Publication (2):
H. Stepankovla et al, "Fe NMR Study of Magnetization Processes in Barium Hexaferrites", Journal of Magnetism and Magnetic Materials, 157/158, 1996, pp. 393-394.

CLAIMS:

1. An NMR sensor, comprising:

a magnetic field generating assembly;

an RF antenna; and

a plurality of ferrite members which couple with RF magnetic fields transmitted or received by the RF antenna.

2. A sensor according to claim 1, wherein a maximum dimension of each of the ferrite members is less than a half wavelength of electromagnetic waves within the ferrite material at the NMR operating frequency.

3. A sensor according to claim 1, wherein the RF antenna comprises a coil which is wound over the ferrite members.

4. A sensor according to claim 1, wherein the magnetic field generating assembly comprises a pair of axially spaced main magnets having opposite pole orientation, and the RF antenna is located axially between the pair of main magnets.

5. A sensor according to claim 1, wherein the sensor is arranged to perform measurements on an external sample outside a space envelope of the magnetic field generating apparatus and the RF antenna.

6. A sensor according to claim 1, wherein the magnetic field generating assembly has a radial gradient which is minimised with respect to variation in a size and a position of the ferrite members.

7. An apparatus for performing borehole measurements, comprising:

an NMR sensor including a magnetic field generating assembly;

an RF antenna; and

a plurality of ferrite members which couple with RF magnetic fields transmitted or received by the RF antenna.

10. An apparatus according to claim 8, further comprising:

a recess formed in the support, the recess having a base and a pair of axially spaced shoulders, wherein the ferrite members are located at least partially in the recess; and

one or more strengthening members which are arranged between the ferrite members, coupled to the base of the recess, and coupled to each shoulder of the recess.

L7: Entry 8 of 8   File: USPT   Oct 28, 1986

DOCUMENT-IDENTIFIER: US 4620155 A
TITLE: Nuclear magnetic resonance imaging antenna subsystem having a plurality of
non-orthogonal surface coils

Abstract Paragraph Left (1):
An NMR antenna subsystem has a plurality of co-planar surface coils, each comprised
of a plurality of segments and elements for tuning the coil to resonance at the
Larmor frequency of a nuclei specie to be investigated. Each coil has circuitry for
selectively detuning that surface coil when at least one other one of the plurality
of surface coils is in use. One of a pair of co-planar surface coils can be utilized
for signal reception and includes a parallel-resonant detuning circuit which
operates only when a relatively large magnitude RF signal is induced by an
excitation signal in a second surface coil. The second surface coil includes a
circuit for detuning that coil except when an externally-provided signal is present;
this signal may be the RF excitation signal itself or another signal provided
simultaneously with the RF excitation signal.

Brief Summary Paragraph Right (1):
The present application relates to surface coil antennae for nuclear magnetic
resonance imaging and, more particularly, to a novel nuclear magnetic resonance
imaging antenna subsystem having a plurality of surface coils disposed in
non-orthogonal relationship, and preferably in the same plane.

Brief Summary Paragraph Right (2):
It is known to use a surface coil as a receiving antenna in an in vivo nuclear
magnetic resonance (NMR) experiment; a surface coil is generally more sensitive to
smaller volumes than the considerably larger volume coils typically utilized with
head and/or body imaging NMR equipment. In the typical NMR experiment, the sample to
be analyzed is immersed in a substantially homogeneous static magnetic field
$B.sub.O$, typically directed along one axis, e.g. the Z axis, of a three-dimensional
Cartesian set of coordinates. Under the influence of the magnetic field $B.sub.O$, the
nuclei (and therefore the net magnetization M) of atoms having an odd-number of
nucleons precess or rotate about the axis of the field. The rate, or frequency, at
which the nuclei precese is dependent upon the strength of the applied magnetic
field and on the nuclear characteristics. The angular frequency of precession
.omega. is defined as the Larmor frequency and is given by the equation:
.omega.=.gamma.B.sub.O, in which .gamma. is the gyromagnetic ratio (constant for
each type of nucleus). The frequency at which the nuclei precess is therefore
substantially dependent on the strength of the magnetic field $B.sub.O$, and increases
with increasing field strength. Because the precessing nucleus is capable of
absorbing and re-radiating electromagnetic energy, a radio-frequency (RF) magnetic
field at the Larmor frequency can be utilized to excite the nuclei and receive
imaging response signals therefrom. It is possible, by superimposing one or more
magnetic field gradients of sufficient strength, to spread out the NMR signal
spectrum of the sample and thereby distinguish NMR signals arising from different
spatial positions in the sample, based on their respective resonant frequencies.
Spatial positions of the NMR signals are determinable by Fourier analysis and
knowledge of the configuration of the applied magnetic field gradient, while
chemical-shift information can be obtained to provide spectroscopic images of the
distribution of a particular specie of nucleus within the imaged sample.

Brief Summary Paragraph Right (3):
For NMR imaging at relatively high static field $B.sub.O$ magnitudes (typically in
excess of 0.5 Tesla (T)), having associated Larmor frequencies greater than about 10

MHz., surface coils utilized as imaging or spectroscopy receiving antennae can be constructed with relatively high quality factor Q, such that most of the resistive loss in the receiving circuit originates in the in vivo tissue sample. This is particularly important as the sensitivity of the NMR experiment requires that the receiving antenna favor the NMR response signal from a particular small excited volume of the sample, while being relatively insensitive to noise currents flowing through the total capture volume of the receiving coil.

Brief Summary Paragraph Right (4):
It is also known that the radio-frequency (RF) fields generated by a simple loop or spiral surface coil are highly non-uniform. The surface coil reception sensitivity, which is essentially the inverse of the excitation field generated during sample irradiation, is likewise non-uniform. Hence, a relatively large RF antenna is required for transmission excitation of the sample to produce a more uniform irradiating RF field. A relatively small, but sensitive, surface receiving coil is utilized with the larger-diameter exciting surface coil.

Brief Summary Paragraph Right (5):
Hitherto, the requirements for a relatively small-diameter receiving surface coil and a relatively large-diameter exciting surface coil has typically required that the NMR system antennae apparatus 10 (see FIG. 1) position the larger-radius R excitation antenna 11 in a first plane, e.g. in the Y-Z plane (for a three-dimensional Cartesian coordinate system having the NMR static imaging field B.sub.O directed in the Z direction), and position the receiving antenna 12, having a diameter r no greater than one-half the exciting antenna radius R, in a second plane, e.g. the X-Z plane, essentially orthogonal to the exciting transmitter first plane, e.g. the Y-Z plane. The essentially orthogonal placement of the exciting and receiving coils 11 and 12 is based upon several phenomena: the need to prevent currents (induced in the receiving coil during the presence of an irradiating RF magnetic field B.sub.x, e.g. in the X direction, for the illustrated transmitting coil in the Y-Z plane) from damaging the sensitive reception preamplifier, typically connected to receive coil terminals 12a and 12b to receive the induced reception signal voltage V.sub.r thereat; the need to prevent the currents induced in surface coil 12 from, in turn, producing an RF magnetic field B.sub.y which would have a component in the X direction if the receive coil 12 were not situated exactly in the X-Z plane and which would cancel out a portion of the excitation magnetic field B.sub.x ; and the need to avoid the electrical coupling of transmitting coil 11 to receiving coil 12 after the excitation of the sample. The currents induced in reception coil 12 can be prevented from damaging the receive coil preamplifier by utilizing resonant circuitry, as at terminals 12a and 12b, to isolate the subsequent preamplifier (not shown) during periods when a large magnitude of an excitation voltage V.sub.t is present at the terminals 11a and 11b of the transmitting antenna. However, the production of an induced RF magnetic field has hitherto only been reduced by the aforementioned essentially orthogonal placement of the two surface coils 11 and 12, and the art has not otherwise considered the problem of surface coil-to-surface coil coupling in the receive mode, which coupling causes criticality in the tuning adjustments of receiving coil 12 due to the relative orientation of coils 11 and 12 and can induce additional noise in the receiving antenna 12 caused by noise currents in the transmitting coil 11.

Brief Summary Paragraph Right (6):
It is especially desirable, to facilitate placement of the antennae during in vivo imaging of a portion of the human anatomy, to have both the transmission excitation surface coil antenna 11 and the response signal receiving antenna 12 in a substantially planar configuration as, for example, described and claimed in application Ser. No. 641,540, filed on even date herewith, assigned to the assignee of the present application and incorporated herein in its entirety by reference. A highly desirable NMR imaging antenna has at least two surface coils, at least one of which is utilized for excitation signal transmission and at least one other one of which is utilized for response signal reception, but which are so decoupled as to be devoid of induced counter fields during excitation irradiation and to be devoid of damping and other deleterious effects during image signal reception.

Brief Summary Paragraph Right (7):
In accordance with the invention, an NMR antenna subsystem has a plurality of co-planar and substantially concentric surface coils, each comprised of a plurality of segments having means interposed between segments for tuning, in conjunction with distributed capacitances, the surface coil to resonance at the Larmor frequency of a nuclei specie to be investigated. Each coil has means, interposed between adjacent

ends of a pair of consecutive segments, for selectively detuning that surface coil when at least one other one of the plurality of surface coils is in use; the detuned coil has substantially no effect upon the at least one other co-planar coil.

Brief Summary Paragraph Right (8):
In a presently preferred embodiment, the subsystem comprises a pair of co-planar surface coils. A first surface coil, of smaller effective radius, is utilized for signal reception and includes a parallel-resonant detuning circuit which operates only when either a switching signal is applied or a relatively large magnitude RF signal is induced in the first surface coil by an excitation signal in a second surface coil, having a larger effective radius than, and surrounding, the first surface coil. The second surface coil includes means for detuning that coil except when an externally-provided signal is present; this signal may be the RF excitation signal itself or another signal provided simultaneously with the RF excitation signal.

Brief Summary Paragraph Right (9):
Accordingly, it an object of the present invention to provide a novel NMR imaging antenna subsystem having a plurality of non-orthogonal, co-planar surface coils.

Drawing Description Paragraph Right (1):
FIG. 1 is a perspective view of an orthogonal two-surface-coil antennae apparatus as utilized in the prior art;

Drawing Description Paragraph Right (2):
FIG. 2 is a schematic diagram of a substantially co-planar NMR surface coil antennae subsystem having a plurality of non-orthogonal surface coils, in accordance with the principles of the present invention;

Drawing Description Paragraph Right (3):
FIG. 3 is a perspective view of a presently preferred embodiment of the non-orthogonal surface coil antennae subsystem of FIG. 2, and is useful in understanding several principles of the present invention, including alternative switching, tuning and other functional implementations therefor; and

Drawing Description Paragraph Right (4):
FIG. 4 is a photograph illustrating an image of the ocular area of a human volunteer, obtained with the novel surface coil antenna subsystem of the present invention.

Detailed Description Paragraph Right (1):
Referring now to FIGS. 2 and 3, a surface coil antennae subsystem 20 or 20' comprises at least two separate surface coils, such as first surface coil 21 and second surface coil 22. The surface coils may be formed upon a suitable insulative substrate 20'a, which may have flexibility properties tailored to allow the co-planar surface coils 21 and 22 to be contoured to the exterior surface of a sample to be investigated by NMR experiments. Each surface coil 21 or 22 is formed of a plurality N of segments, with the respective surface coil conductor segments 23 or 24 having straight, angulated or continuously curved peripheries, as shown by the angulated segments 23a-23h of the octogonal-shaped first, outer surface coil 21 (with N=8) or the continuously-curved arcuate segments 24a-24d of the second, inner surface coil 22 (with N=4). Advantageously, for use with first surface coil 21 acting as an exciting transmission antenna for a nuclei specie providing a re-radiated signal received by second surface coil 22, the average equivalent radius R of the larger surface coil will be at least twice the average equivalent radius r of the smaller surface coil 22.

Detailed Description Paragraph Right (2):
Each of the N surface coil segments 23 or 24 has the ends thereof separated from the adjacent ends of other segments 23 or 24 of the like surface coil. That one of coils 21 and 22 intended for use as a reception coil has one of a plurality N of capacitive coupling elements coupled across each of the N gaps between adjacent segments thereof; thus, reception coil 22 has (N=4) coupling capacitors 25a-25d individually coupled between adjacent ends of different ones of the N=4 segments 22a-22d. Each of capacitors 25 is advantageously of variable value, selected to resonantly-tune the coil 22 to the Larmor frequency of the nuclei to be investigated. A plurality of capacitive elements is desirable to negate the effects of the parasitic capacitances 26a-26d, which are themselves capable of random variations. The received signal is provided between coil ends 22a and 22b to

connector 22c.

Detailed Description Paragraph Right (3):
The surface coil intended for use as an excitation coil has one of a plurality
M=(N-1) of capacitive element 27a-27g individually connected across all but one of
the intersegment gaps. Thus, each of coupling elements 27a-27g is connected across
one of the gaps between the adjacent ends of respective segments 23a-23h of coil 21,
except for the gap between adjacent ends of segments 23a and 23h. An additional, or
N-th, equivalent capacitive element, e.g. capacitive element 27h (shown in broken
line), may be provided only by the parasitic capacitance of a first switching means
28. Capacitances 27 may be fixed or variable and are selected to tune, when means 28
provides a substantially low-impedance, e.g. short, circuit between the ends of
segments 23a and 23h, the coil to the desired excitation frequency, in conjunction
with the second coil segment parasitic capacitances 29a-29h. Each parasitic gap
capacitance 27 is preferably of relatively small value, to detune the large surface
coil away from the desired frequency when means 28 is in a non-conductive (high
impedance, or open circuit) condition.

Detailed Description Paragraph Right (4):
Means 28 can be any selective-conduction network, such as is illustratively provided
by unidirectionally-conducting elements 28a and 28b. Elements 28a and 28b can be a
pair of anti-parallel-connected diodes, if the magnitude of the RF excitation signal
voltage expected across the diodes is sufficiently large and the diode speed is
sufficiently fast to cause each diode to conduct for an appreciable portion of an RF
signal half-cycle. As it is one continuing objective of NMR research to reduce the
magnitude of the RF excitation signal used in in vivo experiments, certain
excitation sequences or power levels may be of inadequate magnitude to cause diodes
28a and 28b to be rendered self-conductive during the excitation portion of an
imaging sequence. An alternative selective-conduction network 28' may then be
required, to provide a low-impedance condition between the ends of two adjacent
segments, during excitation signal transmission and to provide a high-impedance
condition at other times. If network 28' is present, means 28 and capacitance 27b
are removed and capacitance 27h is provided. Means 28' utilizes a pair of RF
switching elements 28' a and 28'b, which may be of the voltage-controlled type, such
as varactor diodes and the like, or may be of the currentcontrolled type, such as
P-I-N diodes and the like, to provide the required low-impedance connection between
the two adjacent ends of a chosen pair of segments, e.g. segments 23b and 23c in the
illustrated example, responsive to an external signal, e.g. switching signal
V.sub.s, which is provided at least during each time interval when an excitation
signal is applied to the surface coil ends 21a and 21b, via connector 21c.
Illustratively, means 28' has a pair of P-I-N diodes 28'a and 28'b in
series-connection between the ends of segments 23b and 23c; the common cathodes of
the two diodes are returned to D.C. common potential through a first RF choke coil
28'c, while each diode anode is connected via another RF choke 28'd or 28'e to a
positive switching control voltage V.sub.s input 28'f. If use of a negative V.sub.s
input voltage is desired, the polarity of both diodes 28'a and 28'b must be
reversed. In either case, it will be seen that, in the absence of signal V.sub.s,
the diodes are in an essentially non-conductive condition and, as capacitance 27b is
then only the small parasitic capacitance of the non-conducting diodes, the larger
surface coil 21 is not resonant and does not appreciably couple to the smaller
surface coil 22. When signal V.sub.s is present, a low impedance appears between the
ends of segments 23b and 23c, effectively completing the coil; the capacitances 27a,
27c-27h and 29a-29h tune the now-complete coil to resonance at the Larmor frequency
of the excitation signal.

Detailed Description Paragraph Right (5):
Means 30, present across one intersegment gap of each surface coil used for signal
reception, provides a parallel-resonant "trap" circuit, for detuning the reception
surface coil and substantially preventing the presence of excitation-frequency
signals at the reception surface coil output, response to induction of a signal in
the reception surface coil at the resonant Larmor frequency of the trap circuit.
Means 30' provides the same "trap" action, responsive to an external signal, as an
alternative to means 30. Thus, reception surface coil 22 has a detuning means 30 or
30' across the gap between two adjacent segments, e.g. between segments 24b and 24c
or between segments 24c and 24d. Means 30 includes an induced-signal sensing means,
such as anti-parallel-connected diodes 30a and 30b, for providing a low-impedance
circuit only if a signal of sufficiently hazardous magnitude (e.g. greater than some
few tenths of a volt, peak) is induced in surface coil 22. Means 30 also includes a
reactive element which is switched into parallel connection across the gap

responsive to the low-impedance condition obtaining in the sensing diodes 30a and 30b; this reactance is of opposite sign to the reactance of the tuning element across the same intersegment gap, and of a value selected to parallelly resonate with the intergap impedance at the Larmor frequency of an associated excitation surface coil antenna. Means 30' utilizes an externally-controlled detuning means, e.g. a P-I-N diode 30'a, which is in RF series-connection with reactive element 30'c across capacitance 25a; a pair of RF chokes 30'd and 30'e are effectively in series with the diode between ground potential and an input terminal 30'f, to allow the diode to conduct (and place element 30'c across capacitor 25a) responsive to an externally-supplied signal, e.g. a voltage +V, being provided at input terminal 30'f. Thus, where (as illustrated) the tuning impedance element across the associated gap is a capacitance 25c or 25a, the impedance element 30c or 30'c is an inductance, of value L aproximately given by: $L=(2.pi.f.sub.L).sup.-2 /C$, where f.sub.L is the Larmor frequency to be excited by the associated excitation surface coil 21 and C is the value of capacitor 25c or 25a. Inductor 30c or 30'c will advantageously be of a value and position such that it has minimal coupling to either reception or excitation surface coils; a toroidal inductor or an inductance formed by a shorted length of coaxial cable, is preferred for avoiding this undesired inductive coupling. It will be understood that the actual value of both capacitor 25c or 25a and inductor 30c or 30'c must be adjusted in situ, respectively, with no excitation present and with excitation present in coil 21, to account for the effects of parasitic impedance of the non-ideal diodes used for switching elements 30a and 30b or element 30'a. Similarly, the value of at least one of capacitances 27 of excitation coil 21 may require adjustment due to the parasitic impedance of the non-ideal switching diodes 28a and 28b, 28'a and 28'b or 30'a. It should also be understood that if surface coils for several different frequencies are "stacked" (as described in the abovementioned co-pending application) to allow simultaneous or sequential NMR experimentation with different species of nuclei, then each coil (either excitation or reception) may require a parallel-resonant trap circuit for each of the total number of involved Larmor frequencies, to prevent induced effects between the various coils if the coil locations and Larmor frequencies are such that coupling is possible. Such additional traps can be provided by one or more additional inductances 32a-32d, each in parallel connection with an associated one of capacitors 27a, 27c, 27e and/or 27g and tuned to the required frequency. Either or both of coils 21 and/or 22 can have additional trap circuits; the values of capacitance in parallel with each trap inductance 32 may, but need not, be of similar magnitude and the value of those capacitors not bridged by a trap inductance can be the same as, or different than, both the trap capacitors, or each other. In generally, similar values may be used to provide a symmetrical radiation/sensitivity pattern to each surface coil antenna, although it should be understood that some NMR experiments may require use of non-identical impedances in any of impedance elements 25, 27, 30 and/or 32, to obtain a particular required antenna characteristic.

Detailed Description Paragraph Right (6):
Referring now to FIG. 4, a photograph of a .sup.1 H image of an axial section of a human volunteer, as imaged with a surface coil subsystem in accordance with the present invention, is shown. The clarity of the details of the human eye and brain, in this 4 mm. thick slice, illustrate the substantial non-interaction of the co-planar antennae of the present invention. The imaging antenna subsystem comprised a single-loop reception coil 22, of about 5 centimeters median radius r, having an inductance of about 190 nanohenries and four segments 24; four capacitors 25 of about 130 picofarads each were used, for .sup.1 H imaging at a Larmor frequency of about 63.5 MHz. in a system having a static field B.sub.O of about 1.5 Tesla. Diodes of the 1N4608-type were used, with a two-turn, 12 millimeter diameter inductance 30c, positioned such that its axis was substantially perpendicular to the common plane of the surface coils. The excitation coil was of eight-segment octogonal shape, having a median spacing of about 25 centimeters between opposite sides and a loop inductance of about 60 nanohenries. Capacitors 27 were about 82 picofarads. Means 28 comprised a pair of Unitrode UM6201-B P-I-N diodes.

Detailed Description Paragraph Right (7):
While several presently preferred embodiments of my novel NMR imaging antenna subsystem with a plurality of non-orthogonal surface coils have been described herein, many modifications and variations will now become apparent to those skilled in the art. For example, other non-orthogonal coil systems, such as one having a volume excitation coil and a surface reception coil, can be equally as well utilized with the detuning means of the present invention. It is my intent to be limited only by the scope of the appending claims and not be the specific details and

instrumentalies presented by way of explanation and illustration herein.

CLAIMS:

1. An antenna subsystem for use in magnetic resonance imaging of selected nuclei in a sample, comprising:

a plurality of substantially planar surface coil antennae disposed with the planes thereof in a non-orthogonal registered relationship;

first means, forming a portion of each of said surface coil antennae to be uitlized for sample excitation with an externally-provided radio-frequency (RF) excitation signal, for causing the associated surface coil antenna to be resonant, at the Larmor frequency of the selected nuclei, responsive only to an externally-provided switching signal; and

second means, forming a portion of each of said surface coil antennae to be utilized for response signal reception, for detuning the associated surface coil antenna at least when a radio-frequency signal is induced therein by the RF excitation signal in one of said excitation antennae.

2. The antenna subsystem of claim 1, wherein said externally-provided switching signal is the radio-frequency excitation signal itself.

3. the antenna subsystem of claim 2, wherein each excitation surface coil antenna comprises a conductive member having at least one gap formed therein; and said first means comprises: at least one switching element connected between adjacent conductive member ends defining a selected one of said at least one gap, the at least one switching element being (1) enabled to a relatively low impedance condition responsive to the presence of said externally-provided radio-frequency signal at said excitation surface coil and (2) disabled to a relatively high-impedance condition responsive to the absence of said externally-provided radio-frequency signal at said excitation surface coil antenna.

4. The antenna subsystem of claim 3, wherein said at least one switching element comprises a pair of antiparallel-connected diodes coupled across said selected gap.

5. The antenna subsystem of claim 1, wherein said externally-provided switching signal is a signal different from said radio-frequency excitation signal.

6. The antenna subsystem of claim 5, wherein each of said excitation surface coil antennae comprises a conductive member having at least one gap formed therein; and said first means comprises: at least one switching element connected across one conductive member gap and responsive respectively to the presence and absence of an electrical parameter for attaining respective low-impedance and high-impedance conditions; means for receiving the externally-provided switching signal; and means for connecting the switching signal receiving means to said at least one switching element to cause said switching element to switch between said low-impedance and high-impedance conditions responsive to selected ones of the presence and absence of said switching signal.

7. The antenna subsystem of claim 6, wherein said at least one switching element is at least one varactor diode and said switching signal is a switching voltage.

8. The antenna subsystem of claim 6, wherein said at least one switching element is at least one P-I-N diode and said switching signal is a switching current.

9. The antenna subsystem of claim 1, wherein a pair of non-orthogonal surface coil antennae are co-planar to one another.

10. The antenna subsystem of claim 9, wherein the centers of the pair of surface coil antennae are substantially identical.

11. The antenna subsystem of claim 9, further comprising an insulative substrate supporting said pair of surface coils upon a surface thereof.

12. The antenna subsystem of claim 1, wherein each of said plurality of surface coil antennae comprises; a plurality of conductive segments arranged with each of a like plurality of intersegment gaps between adjacent pairs of segments; and further

including at least one reactive means coupled across at least one intersegment gap for tuning the associated surface coil antenna to the Larmor frequency of a nuclei species to be imaged with said subsystem.

13. The antenna subsystem of claim 12, wherein at least one of the at least one reactive means is a variable reactance.

14. The antenna subsystem of claim 13, wherein the variable reactance is a variable capacitive reactance.

15. The antenna subsystem of claim 12, wherein said at least one reactive means is a capacitive element.

16. The antenna subsystem of claim 15, wherein an inductive element is coupled in parallel with at least one of the capacitive elements, the inductive element having an inductive reactance selected to resonate with the reactance of the associated capacitive element at a predetermined frequency.

17. The antenna subsystem of claim 16, wherein the predetermined frequency is different than the Larmor frequency to which the surface coil antenna is tuned.

18. The antenna subsystem of claim 1, wherein each signal reception antennae comprises a conductive member having at least one gap formed therein; and said second means comprises: an element of a first impedance type connected across said gap; an element of a second impedance type, of magnitude selected to resonate with said first impedance element at the Larmor frequency of the signal provided to the associated excitation antenna; and means, connected in series with said second impedance element across said gap, for selectively connecting said second impedance element in parallel with said first impedance element responsive only to said radio-frequency signal induced in said reception antenna.

19. The antenna subsystem of claim 18, wherein said first reactive element is a capacitive element; and said said second reactive element is an inductive element.

20. The antenna subsystem of claim 19, wherein said connecting means comprises a pair of unidirectionally-conducting switching elements coupled in antiparallel connection between one gap-forming end of said conductive member and that end of said second impedance element furthest from the end thereof connected to the other gap-forming end of said conductive member.

21. The antenna subsystem of claim 19, wherein said connecting means comprises: at least one switching element coupled between one gap-forming end of said conductive member and that end of said second impedance element furthest from the end thereof connected to the other gapforming end of said conductive member and responsive to the presence or absence of a control signal for providing an associated low-impedance or high-impedance condition between said ends; and means for providing said control signal to said switching element from a source external to said antenna subsystem.